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## The current status of new Czech corrosion fatigue evaluation proposal for WWER nuclear power plants

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### Abstract

Presented paper introduces an innovative principle of fatigue life assessment suggested for WWER nuclear power plants. The subject of this work is to take into account the corrosion environment influence in actual methodology of low-cycle fatigue (LCF) assessment and prediction. The aim of this paper is to summarize the current status of the Czech proposal of corrosion fatigue assessment and prediction. The first project focused on base steel materials, which are used in primary circuit of WWER-440, started in 2010. The basic idea of Czech environmental fatigue correction factor has been introduced on international PVP conference in 2013. The new project linked to the previous one is focused on the additional area of welding joints. Theoretical base is completed by experimental verifications of proposed environmental correction factor. The subject of actually running theoretical-experimental program covers similar metal welds of austenitic stainless steel 08CH18N10T and results will be available in 2015. Moreover LCF tests in corrosion environment of dissimilar metal welds are under preparation. Experimental work is based on LCF strain-controlled tests in primary water environment of WWER-440.

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**Keywords:** low-cycle fatigue; environmental factor; austenitic stainless steel; welds; nuclear power plant

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## 1. Introduction

It is well known that initiation and growth rate of fatigue crack could very strongly depend on local environment. In general corrosion environment decreases the number of cycles to initiation and increases the crack growth rate. The measure of such influence is done on one side by corrosion environment aggressiveness and on the other side on corrosion resistance of material. In the frame of technical public, the influence of environment on fatigue life is not a new topic, but in the last two decades this phenomena is increasingly discussed in the area of nuclear energy.

The decrease of fatigue life due to primary water environment is generally realized by so called fatigue life environmental correction factor ( $F_{en}$ ). Such correction factor was originally introduced in NUREG documents (2007), as results of large experimental program of Argonne National Laboratory-ANL (2011). The environmental correction factor  $F_{en}$  is defined as a ratio of fatigue life in air at reference temperature to fatigue life in water at operating temperature:

$$F_{en} = N_{air, RT} / N_{water} \quad (1)$$

Such way defined environmental correction factor can't be directly used for fatigue life assessment and prediction under operating conditions of WWER nuclear power plants. Reasons are lying on the side of different way of fatigue life assessment and prediction, which is used on the WWER power plants. Direct application of  $F_{en}$  values leads to unrealistic conservative results of estimated allowed number of cycles to fatigue crack initiation. Moreover, the ANL low-cycle fatigue (LCF) data in corrosion environment weren't measured for materials of primary circuit of WWER power plants.

Presented paper introduces an innovative principle of fatigue life assessment suggested for WWER power plants. The subject of this work is to take into account the corrosion environment influence in actual methodology of low-cycle fatigue assessment and prediction. The aim of this paper is to summarize the current status of the Czech proposal of corrosion fatigue assessment and prediction. Assessment procedures used for fatigue life evaluation are stated in NTD A.M.E. standard (2013). The purpose is to take into account the influence of primary water corrosion environment on fatigue life of components and piping for WWER power plants.

## 2. Czech alternative approach for WWER

Considering the Long Term Operations (LTOs) of WWER power plants, the modification of NUREG proposed  $F_{en}$  computation should be found and experimentally verified. The first project focused on base steel materials, which are used in primary circuit of WWER-440, started in 2010. The new actual project linked to the previous one is focused on the additional area of welding joints. The basic idea of Czech environmental fatigue correction factor was firstly suggested in 2010 by Vlček (2010) and after three years later introduced on international PVP conference by the same author (2013). Decreasing of fatigue life has been observed when the synergic effect of next parameters and their critical values are met: (i) strain amplitude, (ii) strain rate, (iii) operating temperature, (iv) dissolved oxygen and (v) sulphur content (not for austenitic steels). The redefinition of environmental correction factor  $F_{PR}$  was introduced as a ratio of total strain amplitude in air at operating temperature condition to total strain amplitude in water at operating temperature condition, see Vlček (2010):

$$F_{PR} = \epsilon_{at air} / \epsilon_{at water} \quad (2)$$

where  $\epsilon_{at air}$  is the total strain amplitude in air at operating temperature,  $\epsilon_{at water}$  is the total strain amplitude in water at the same operating temperature.

The whole idea of environmental factors is simply defined in Fig. 1. Brief summary of discussed factors is tabulated in Table 1. Information is completed by the references in which the definitions were introduced. In addition, the minimal values of environmental factors are shown for austenitic stainless steels together with year of publication.

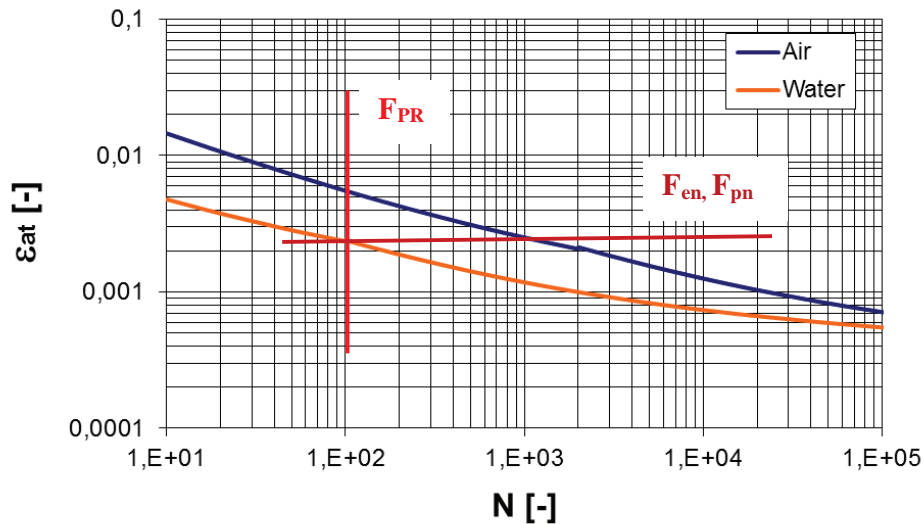
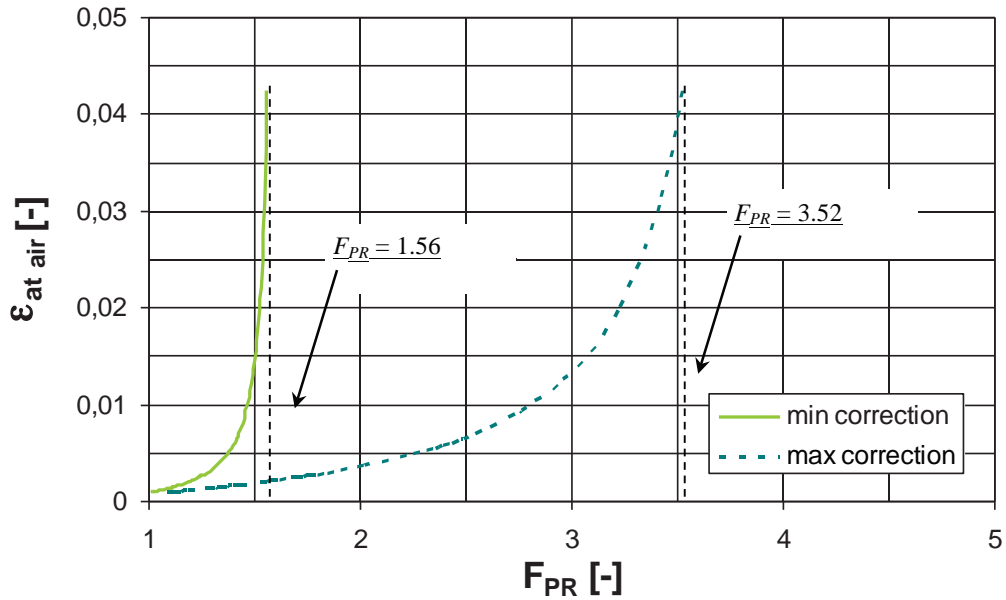


Fig. 1 The base idea of environmental factor definitions

Based on the new definition, there were constructed dependences of total strain amplitude vs. environmental correction factor  $F_{PR}$ . The environmental correction factor is related to the total strain coming not from fatigue design curve, but from fatigue curve without the application of safety factors on stress  $n_s = 2$  and number of cycles  $n_N = 10$ . Dependences of  $\varepsilon_{at\ air}$  vs.  $F_{PR}$  were constructed for the case of minimal (theoretical) influence and maximal (theoretical) influence of primary water environment on fatigue life. The example of such dependences for austenitic stainless steels is in Fig. 2. Theoretical minimal and maximal influence of corrosion environment on fatigue life is covered by design fatigue curves (so called S-N curves) proposed by Filatov and Evropin (2004).

Table 1. Summary of environmental factors completed by minimal values for austenitic stainless steels.

Country	Document	Mark	Definition	Min. value
Japan	JSME S NF1 (2009)	$F_{en}$	$N_{airRT} / N_{water}$	1 (2009)
USA	NUREG/ANL (2007, 2011)	$F_{en}$	$N_{airRT} / N_{water}$	2.08 (2007) 1 (2011)
Russia	VERLIFE (2011)	$F_{pn}$	$N_{airRT} / N_{water}$	2.54 (2011)
Czech Rep.	NTD A.M.E. (2013)	$F_{PR}$	$\varepsilon_{at\ air} / \varepsilon_{at\ water}$	1 (2010)

Fig. 2 Dependences of  $F_{PR}$  on total strain amplitude in air (austenitic stainless steels)

With the aim of direct application in the frame of actual mathematical description, which describes relations of S-N design curves, the coefficient for water corrosion environment  $\varphi_{PR}$  can be defined as the reciprocal value of  $F_{PR}$ :

$$\varphi_{PR} = 1/F_{PR} \quad (3)$$

Finally, the allowed so called fictive stress amplitude in water  $[\sigma_{aF}]_{water}$  is computed as allowed fictive stress amplitude in air and operational temperature  $[\sigma_{aF}]_{air}$  multiple by the coefficient for water corrosion environment  $\varphi_{PR}$ :

$$[\sigma_{aF}]_{water} = [\sigma_{aF}]_{air} \cdot \varphi_{PR} \quad (4)$$

### 3. Experimental verification

For experimental verification, low-cycle fatigue tests of smooth round bar specimens were performed in primary water environment. As an experimental material, the austenitic steel 08CH18N10T (U.S. equivalent AISI 321) of primary circuit of WWER 440 was chosen. Chemical composition is shown in Table 2. Table 3 shows the minimal guaranteed tensile properties at room temperature. Strain controlled LCF tests were performed at 320°C under applied pressure of 12.5 MPa. The strain rate was set to 0.002%/s with  $R = -1$ , where  $R$  is the strain ratio. Results of LCF tests in primary water clearly show decrease in fatigue life in comparison with the same tests performed in air. It should be noted that the verification experiments were done in limited range.

Table 2. Chemical composition of 08CH18N10T steel in wt%.

C	Cr	Ni	Mo	Ti	Si <sub>max</sub>	P <sub>max</sub>	S <sub>max</sub>
0.03	16.91	9.40	0.10	0.22	1.00	0.045	0.03

Table 3. Minimal guaranteed mechanical properties, room temperature.

E [MPa]	R <sub>m</sub> [MPa]	R <sub>p0.2</sub> [MPa]	Z [%]	A <sub>5</sub> [%]
201000	490	196	40	38

Note) E: Young modulus, R<sub>m</sub>: ultimate strength, R<sub>p0.2</sub>: yield strength, Z: contraction, A<sub>5</sub>: elongation

On the basis of LCF results the experimental dependencies of  $F_{PR}$  on the total strain amplitude in air was constructed. These dependencies were plotted together with the theoretical dependencies, which were suggested with using of maximal and minimal environmental corrections. The comparison of proposed theoretical dependencies with experimental ones is in the Fig. 3. LCF tests at lower strain amplitudes have not been performed, because the lower the strain amplitude, the less influence on fatigue life can be expected. Due to comparison of experimental and theoretical dependences of  $F_{PR}$  on the total strain amplitude in air, it is evident that the maximal theoretical proposed correction doesn't correspond to the experimental results. The large gap between the proposed maximal correction and the maximal experimental one is done mainly by different level of strain rate. To the contrary, the curve for minimal proposed correction lies between both experimental curves. The real influence of water environment is much closer to the proposed minimal correction. It can be noted that the experimental results were obtained only on the base material, it means without weld joints. The next LCF tests in primary water on welds are running.

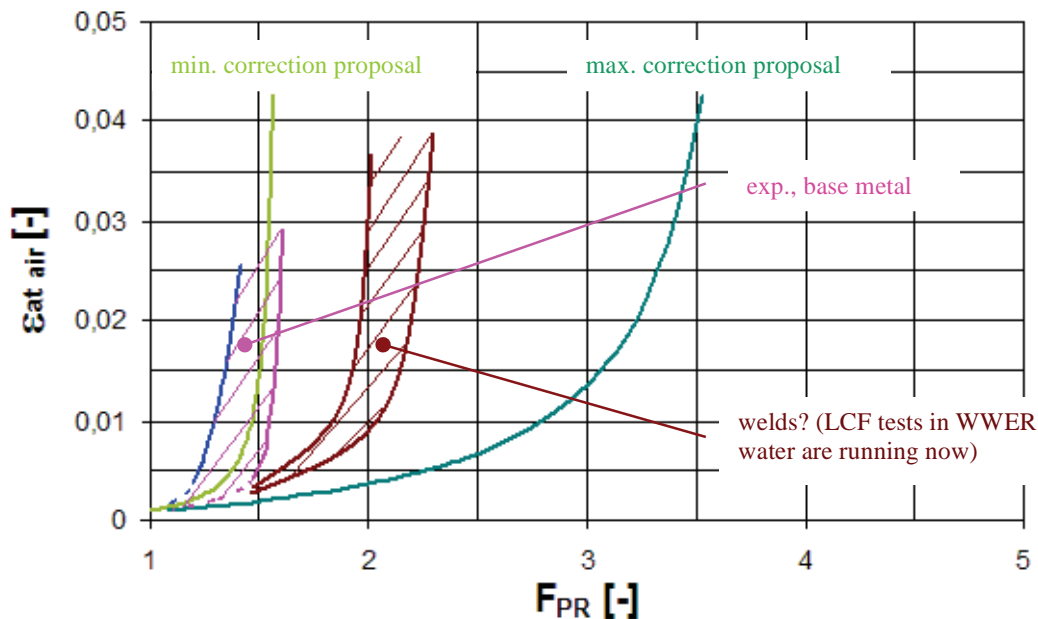


Fig. 3 Theoretical and experimental dependences of  $F_{PR}$  on total strain amplitude in air

#### 4. Conclusion

The environmental correction factor  $F_{en}$  originally introduced in NUREG documents can't be directly used for fatigue life assessment and prediction under operating conditions of WWER nuclear power plants. Reasons are lying on the side of different way of fatigue life assessment and prediction, which is used on the WWER power plants. Moreover the ANL low-cycle fatigue data in corrosion environment weren't measured for materials of primary circuit of WWER power plants. Considering the long-term operations of WWER power plant the modification of NUREG proposed  $F_{en}$  computation was found and experimentally verified. Therefore the redefinition of environmental correction factor  $F_{PR}$  was introduced as a ratio of the total strain amplitude in air at operating temperature to the total strain amplitude in water at operating temperature.

LCF results in corrosion environment on WWER materials are missed or rather limited. Our experiments in primary water on base material, type of austenitic stainless steel 08CH18N10T, clearly showed decrease in fatigue life in comparison with the same tests in air. Apparently the situation related to the current lifetime assessment is not so dramatic. The reason can be seen in the conservative approach, when the minimal

guaranteed tensile mechanical properties are taken for fatigue curve of Langer's type construction. Due to this fact the computational design fatigue curve in air of Langer's type has lower position than real measured data from LCF tests in water. But from this point of view the safety margins introduced by safety factors on stress and on number of cycles are partially used also for environmental aspects. Thus the fatigue environmental correction by  $F_{PR}$  is recommended with the aim to keep the required safety margin.

The environmental correction by  $F_{PR}$  was suggested as a general procedure for base metals as well as for welds. The subject of actually running theoretical-experimental program covers similar metal welds of austenitic stainless steel 08CH18N10T. Moreover LCF tests in corrosion environment of dissimilar metal welds are under preparation.

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